

Dynamic refining control model for LD converter

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ABSTRACT

A mathematical model for the dynamic refining control of the LD Converter is presented. Equations representing the reaction kinetics are formulated using the oxygen demand function. The amount of oxygen accumulated in LD Converter, which is calculated from the oxygen balance by using exhaust gas data, corresponds to the amount of FeO, Fe₂O₃, and MnO in the slag during blowing. With the control of the refining reaction with oxygen balance carbon, phosphorus and manganese contents of steel and the total iron content of slag at blow end were controlled at preferable levels and their fluctuations were remarkably reduced. The equations were coupled with appropriate thermal balance equations. The resulting set of non-linear first order equations have been numerically solved to predict the reaction path in the converter as a function of the operating conditions like oxygen blowing rate, lance height, iron ore, limestone additions rates etc. With continuous on line data feeding from the converter facilities like substance systems and waste gas analysers the entire converter operation could be automated. The model works on a simple micro computer and could be easily incorporated on to the on-line control circuit of the Converter.

INTRODUCTION

The extensive use of automatic-control techniques for steel making processes has expanded considerably in recent years. This has been made possible because of improved expertise in the data acquisition from the complex high temperature processes and consequently, there has been an added stimulus to develop more accurate mathematical models to simulate process stages. At present there are two basic types of models that are applied to oxygen steel making processes, known as 'Static' and 'Dynamic' mathematical models simulating process behaviour.

Static models comprise a set of heat and mass balance equation that enable the prediction of material demand from known initial conditions of charge

composition, weight and temperature to give the required end-point specification of steel carbon content, temperature and weight. In contrast Dynamic models^[1-3] comprise differential equations which describe the rate of change of bath and slag composition throughout the blowing stage and are designed to take into account variations in blowing conditions and sequence of additions as continuous sensors feed back data to the control system throughout the process. Thus, it is within the capability of the Dynamic model to prescribe the appropriate corrective action to ensure that the trajectory of the process path achieves the required end-point target for steel temperature and carbon content in particular.

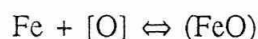
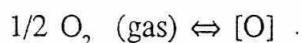
The reactions taking place in the steel making process can be divided into sequential steps as mass transfer of reactants to the phase boundary, interfacial chemical reaction, and mass transfer of reaction products away from the phase boundary. At the temperatures prevailing during steel making, the chemical reaction step is much faster than the other step described above and the refining reactions are effectively limited by mass transfer. In this paper an attempt has been made to develop a Dynamic model which takes into consideration the changes in bath temperature on reaction kinetics and predicts the composition of slag, metal and gas as a function of time as the blowing progresses. In a true control system the output/predictions of the model can be compared to that of the actual composition of the metal in the bath with the help of sensors and corrective actions taken on-line.

THEORY

According to the multicomponent mixed transport control theory^[4], an instantaneous Thermodynamic equilibrium is assumed to exist at various metal-gas-slag interfaces and the rates of reaction are governed by transport of species present to or away from the interface.

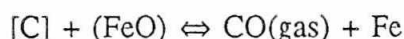
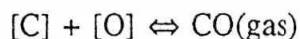
Refining Reactions

During LD steel making, the oxygen required for the refining reactions is supplied in the gaseous form and both metal and slag are initially oxidised :



The actual distribution of Oxygen between slag and metal is easily determined, since it is a function of a number of variables, including lance height and oxygen flow rate. The principal refining reaction is, the removal of carbon :

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The basic thermodynamic data for the above reactions is well established, and the equilibrium carbon and oxygen contents may be readily calculated for all the temperatures and pressures encountered during steel making^[5].

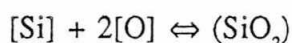
Decarburisation Mechanism

Decarburisation is assumed to take place principally in the slag-metal-gas emulsion, which occupies a large fraction of the converter volume during a major part of the blow. Oxygen is initially delivered to the bath via the jet impingement zone. This oxygen enriched material is then swept away from the interaction zone by the combined effect of rising CO bubbles, natural convection and the absorption of energy from the oxygen jet, thus exposing a further layer of metal to the oxygen jet, and the pattern is repeated. After the formation of the considerable amount of oxidized metal over the bath, the jet helps in dispersing metal droplets in the slag phase. Refining of these metal droplets takes place as they travel in the gas rich slag-metal emulsion and join back the bulk metal. Oxygen is transferred to the droplets by unsteady state diffusion and a high degree of supersaturation with respect to the $[C] + [O] \rightarrow CO$ reaction can be achieved.

Heterogeneous nucleation of carbon monoxide occurs when the droplet comes into contact with rising CO bubbles. Alternatively homogeneous nucleation of CO is possible, if the oxygen supersaturation is sufficiently high. Homogeneous nucleation may take place explosively thus creating a finer dispersion of the metal. In order to reduce the carbon level significantly, each droplet must pass through the complete cycle several times.

Silicon Removal

In accordance with thermodynamic predictions, the removal of silicon is usually completed relatively early in the blow. The reactions may be represented by the following equations :



According to the above reactions all the oxygen blown in the bath reacts with silicon during the initial period of blowing. In the model it is assumed that

silicon is dropped till the bath silicon reaches a equilibrium level or till that time when the slag layer of specified thickness is formed. After the formation of slag layer the droplets generated due to the impingement of the jet disperses into the slag and the droplet-slag reactions are started. For the simplicity of the model, it is assumed that the droplets of equal sizes are formed.

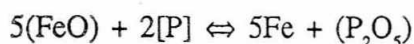
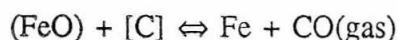
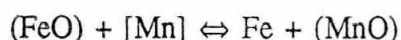
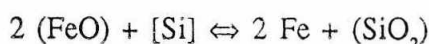
The droplet-slag interface is considered to be the prime location for the oxidation reactions taking place, i.e. oxidation of Silicon, Manganese, Carbon and Phosphorus. It is assumed that the lime dissolution takes place in the slag according to the concentration of Silica and the pre-set basicity (2.5 to 3.0) of the slag is maintained.

For the purpose of the calculation of the amount of each element oxidised it is assumed that in a particular time step whatever is injected reacts with Fe forming FeO initially and the FeO is distributed equally among the droplets ejected. This FeO in the droplets/slag in turn reacts with the elements C, Si, Mn and P depending on their respective thermal equilibrium with FeO and rest of the elements. All these reactions are assumed to be taking place during the travel of the droplet in the slag-gas-metal emulsion.

MODEL FORMULATION

According to the the multicomponent mixed transport control theory an instantaneous thermodynamic equilibrium is assumed to exist at various metal-slag-gas interfaces and the rates of reactions are governed by the transport of the species present to or away from the interface.

The concentration of species present is obtained from equilibrium at the interface for the reactions :



For each of the above reactions at the slag-metal interface it is possible to write the relevant equilibrium constants which relate the interfacial concentrations of components, since the reactions are assumed to take place quickly, at the high temperatures of steel making. Equilibrium constants for the above mentioned reactions can be written as :

$$K_{Si} = \frac{\gamma_{SiO_2} \cdot X^i_{SiO_2}}{\gamma_{FeO^2} \cdot f_{Si} \cdot X^i_{FeO^2} \cdot X^i_{Si}} \quad \dots 1$$

$$K_{Mn} = \frac{\gamma_{MnO} \cdot X^i_{MnO}}{\gamma_{FeO} \cdot f_{Mn} \cdot X^i_{FeO_2} \cdot X^i_{Mn}} \quad \dots 2$$

$$K_c = \frac{PCO}{\gamma_{FeO} \cdot f_c \cdot X^i_{FeO} \cdot X^i_C} \quad \dots 3$$

$$K_p = \frac{\gamma_{P_2O_5} \cdot X^i_{P_2O_5}}{\gamma_{FeO^5} \cdot f_{p^2} \cdot X^i_{FeO^5} \cdot X^i_{p^2}} \quad \dots 4$$

Heterogeneous reactions such as the above can be divided into sequential steps, mass transfer of reactants to the phase boundary, interfacial chemical reaction and the mass transfer of reaction products away from the phase boundary. As mentioned earlier the chemical reaction step is much faster than the other involving diffusion, and that the refining reactions are effectively rate controlled/limited by the mass transfer.

Knowing the rate of mass-transfer of each of the reactants (FeO, C, Si, Mn and P in the model), it is possible to calculate the bulk-metal composition at a particular time during blowing.

The mass transfer coefficient of the individual elements is calculated using the Rang-Marshall correlation [6].

$$Nu = 2.0 + 0.6(Re)^{1/2} (Sc)^{1/3}$$

The change in the bulk composition over a time interval 'dt' is given by the conservation equation. Applying the conservation equation for the four elements considered in the model.

$$\frac{d}{dt} ({}^nSi) = \frac{- D_{Si} \cdot A^i}{V^m} (X^m_{Si} - X^i_{Si}) \quad \dots 5$$

$$\frac{d}{dt} ({}^nMn) = \frac{- D_{Mn} \cdot A^i}{V^m} (X^m_{Mn} - X^i_{Mn}) \quad \dots 6$$

$$\frac{d}{dt} ({}^nC) = \frac{- D_C \cdot A^i}{V^m} (X^m_C - X^i_C) \quad \dots 7$$

$$\frac{d}{dt} ({}^nP) = \frac{- D_P \cdot A^i}{V^m} (X^m_P - X^i_P) \quad \dots 8$$

Similarly rate controlling equation for the transfer of FeO to the interface can be written as

$$\frac{d}{dt} (n_{\text{FeO}}) = \frac{-D_{\text{FeO}} \cdot A^i}{V^s} (X_{\text{FeO}}^s - X_{\text{FeO}}^i) \quad \dots 9$$

The mole balance equation for the elements Si, C, Mn and P against FeO consumed can be written as the following :

$$\frac{-D_{\text{FeO}} \cdot A^i \cdot Dt}{V^s} (X_{\text{FeO}}^s - X_{\text{FeO}}^i) = 2(n_{\text{Si}}^{\text{in}} - n_{\text{Si}}^f) + n_{\text{Mn}}^{\text{in}} - n_{\text{Mn}}^f + n_{\text{C}}^{\text{in}} - n_{\text{C}}^f + 2.5(np^{\text{in}} - np^f)$$

From the above equation

$$X_{\text{FeO}}^i = \frac{V^s}{D_{\text{FeO}} \cdot A^i \cdot Dt} [2(n_{\text{Si}}^{\text{in}} - n_{\text{Si}}^f) + n_{\text{Mn}}^{\text{in}} - n_{\text{Mn}}^f + n_{\text{C}}^{\text{in}} - n_{\text{C}}^f + 2.5(np^{\text{in}} - np^f)] + X_{\text{FeO}}^s \quad \dots 10$$

For the transfer (oxidation) of each element from metal phase to slag phase the corresponding increase in Oxides in slag phase can be written as :

$$n_{\text{SiO}_2}^f = n_{\text{Si}}^{\text{in}} - n_{\text{Si}}^f + n_{\text{SiO}_2}^{\text{in}} \quad \dots 11$$

$$n_{\text{MnO}}^f = n_{\text{Mn}}^{\text{in}} - n_{\text{Mn}}^f + n_{\text{MnO}}^{\text{in}} \quad \dots 12$$

$$n_{\text{CaO}}^f = 3(n_{\text{PO}}^f + n_{\text{SiO}_2}^f) \quad \dots 13$$

$$np^f = n_{\text{P}}^{\text{in}} - n_{\text{P}}^f + np^{\text{in}} \quad \dots 14$$

The above 14 equations are solved simultaneously for X_{Si}^i , X_{C}^i , X_{Mn}^i , X_{P}^i , X_{FeO}^i , n_{C}^f , n_{Si}^f , n_{Mn}^f , np^f , $n_{\text{SiO}_2}^f$, n_{PO}^f , n_{MnO}^f and n_{CaO}^f . At each time step the mass balance is carried out and the molar composition of slag and metal phases are modified. The interfacial area which is critical in the above calculations, is calculated based on the number of droplets generated and dispersed into the slag-metal-gas emulsion. The number of droplets generated is calculated from the amount of metal splashed with the momentum of the jet using the Rang-Rammlers sampling correlation^[7].

RESULTS

The predicted compositional changes with respect to C and Si during the course of blowing is shown in Fig. 1. The decarburisation rate curve which is an indication of the blowing profile in the converter, is predicted using the above described model in Fig. 2. The model predicted path is similar to the normal converter practice^[3], wherein the decarburisation rate increases to a maximum in the initial stages, attains a plateau for some time and decreases

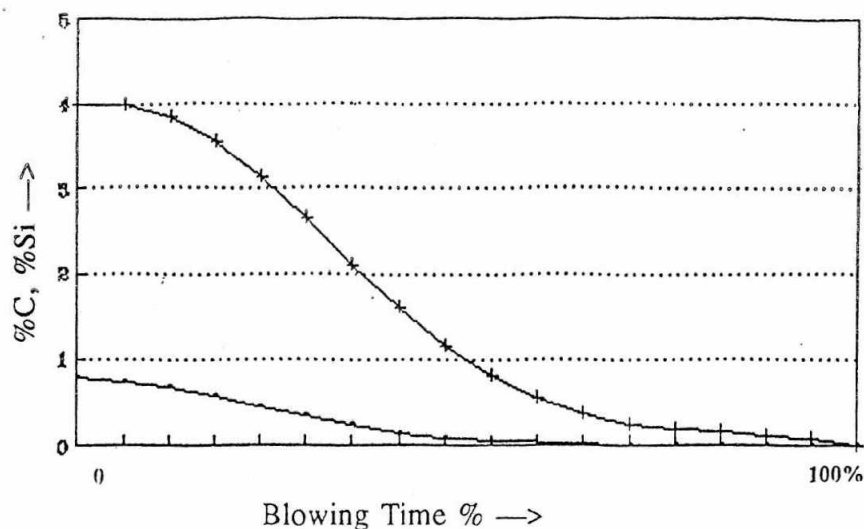


Fig. 1. Predicted compositional change of carbon and silicon during the blowing practice.

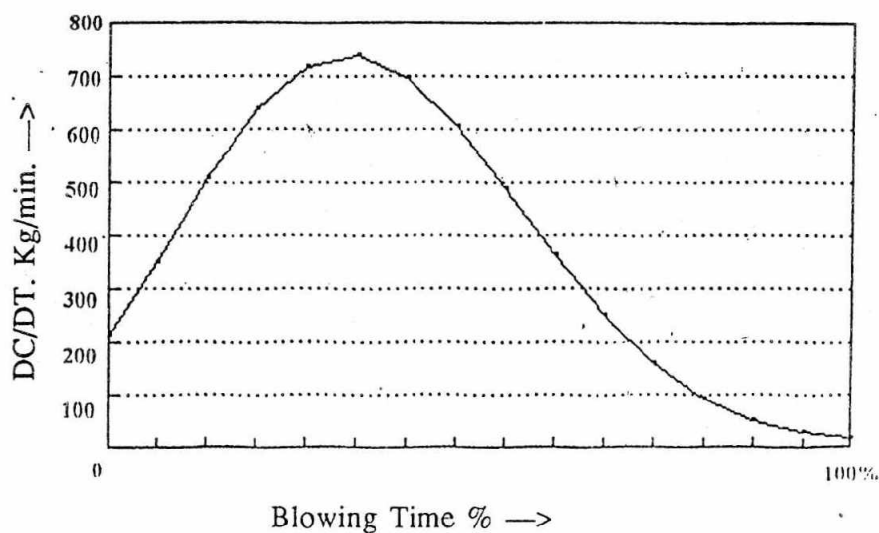


Fig. 2. Predicted decarburisation rate curve for the particular blowing practice simulated in the model.

gradually towards the end of the blow. But as could be seen from the results of decarburisation the decarburisation rate predicted by the model is lower than the usual practice observed in the industrial practice. This may be due to the anomaly in the calculation of the weight of the metal splashed due to the impinging jet and the calculation of the interfacial areas in the model. This could be overcome by introducing a process parameter into the model which

could take care of the deficiency. This process parameter would be dependant on the parameters like refractory profile in the converter, lance configuration and the blowing practice. After further fine tuning of the present model with the industrial data this model could be used on the control circuit of the converter.

NOMENCLATURE

D = Diffusion Coefficient	f = Henrian Activity Coefficient
K = Equilibrium Constant	A = Interfacial Area
X = Mole fraction	dt = time step
n = No. of moles	Nu = Nusselt Number
V = Volume	Re = Reynolds Number
γ = Activity Coefficient	Sc = Schmidt Number

SUPERSCRIPT

M = Metal phase	in = initial
S = Slag Phase	f = final
i = Slag-metal interface	int = interface

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